Three-dimensional Modeling of Optical Turbulence

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Abstract

Optical turbulence is the fluctuation of density and hence refractive index in the atmosphere. It is the phenomenon that causes stars to twinkle and acts to defocus laser beams which reduces the beam's effective range. A means of forecasting optical turbulence has been devised using a two-tiered modeling approach. The first level of the model is a mesoscale numerical weather prediction model that forecasts the mean quantities of wind, temperature, and relative humidity on a grid spacing of approximately 4-30 km in the horizontal and 300-1000 m in the vertical. Since optical turbulence occurs typically on the scale of tens of meters in the vertical, a second level of model is used to parameterize the refractive index structure constant (a measure of optical turbulence) based on the mean quantities predicted by a mesoscale weather model. This combination was put to use in the 1999 Scintillometer Atmospheric Test held in New Mexico. During the experiment, real-time forecasts of optical turbulence were produced on the NAVO Cray C-90 and transmitted via FTP to the meteorologist in charge of each day's pre-flight weather briefing. This represented the first "operationally" produced optical turbulence forecasts. The optical turbulence forecasts were enthusiastically received and incorporated into the pre-mission weather briefing. The exercise of the models resulted in an increase in the system robustness and sensitivity.

Introduction

Optical turbulence is the fluctuation of density in the atmosphere. It is the phenomenon that causes stars to twinkle. In astronomy, optical turbulence is an important consideration because it affects the performance of large telescopes. Likewise it also acts to defocus laser beams which reduce their effective range. Forecasting optical turbulence in the free atmosphere is difficult because the physics that cause its formation and propagation are still not fully understood and it occurs on spatial scales (~ tens of meters) in the vertical that can not be explicitly resolved by current operational high-resolution numerical weather prediction models.

Both Bougeault et al. (1995) and Walters and Miller (1999) have attempted to produce optical turbulence forecasts using mesoscale models with parameterizations for optical turbulence. Bougeault et al (1995) used a version of the Meteo-France limited-area operational numerical weather prediction model, PERIDOT (Imbard et al. 1987) coupled with the Bougeault and Lacarrere (1995) turbulence production model. Walters and Miller (1999) used the turbulent kinetic energy (tke) output from the navy's Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS) (Hodur 1987). In order to produce optical turbulence forecast values of the proper order of magnitude in the free atmosphere, Walters and Miller (1999) found they had to alter the Mellor and Yamada (1982) tke parameterization used in COAMPS. The change they made involved altering the ratio of thermal to momentum diffusivity to allow tke produced by mechanical turbulence not to be damped out by the thermal stability that is prevalent on large scales in the free atmosphere.

In this paper another method for coupling a parameterization of optical turbulence with a numerical weather prediction model will be described and its real-time application in support of the 1999 Scintillometer Atmospheric Test (SAT) in New Mexico will be demonstrated.

Model Description

Optical turbulence is usually quantified by C_n^2, the structure constant for optical index of refraction fluctuations. Tatarski (1971) presents a formulation for C_n^2,

$$C_n^2 = \left(79x10^{-6}\,\frac{P}{T^2}\right)^2 C_T^2\,, \tag{1}$$

where P is pressure in mb, and T is the temperature in K. C_T^2 is the temperature structure constant and is given by

$$C_T^2 = a^2\left(\frac{K_H}{K_M}\right)L^{4/3}\left(\frac{\partial q}{\partial z}\right)^2 \tag{2}$$

where K_H and K_M are the eddy diffusivity coefficients for heat and momentum respectively, a^2 is a constant set to 2.8, q is the potential temperature in K, z is the height in meters, and L is the outer scale of the turbulence. The ratio $\frac{K_H}{K_M}$ is usually set to 1. All of the variables in eqs. (1) and (2) except one are available as output from most mesoscale numerical weather prediction models. The one exception is L. Both Walters and Miller (1999) and Bougeault et al. (1995) used tke values to parameterize L. The parameterization for L used here is one determined by Dewan et al. (1993) who statistically related optical turbulence to observed wind shear by

$$\log L^{4/3} = 0.1*(1.57+40S) \qquad \text{(troposphere)} \tag{3}$$

$$\log L^{4/3} = 0.1*(0.503+51.2S) \qquad \text{(stratosphere)} \tag{4}$$

where S is the horizontal wind shear given by

$$S = \left(\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right)^{1/2} \tag{5}$$

where u is the x-direction wind component and v is the y-direction wind component. Dewan et al (1993) developed these statistical relationships from observations from smoke trails and correlated them to wind observations measurements spaced 300m apart in the vertical. The Dewan et al. (1993) parameterization is thus easily adapted to mesoscale numerical weather prediction models.

The mesoscale model used in conjunction with the Dewan et al (1993) optical turbulence parameterization is the National Center of Atmospheric Research/Penn State University Mesoscale Model 5 (MM5). This is the same model that is run operationally for several theaters by the Air Force Weather Agency. Details regarding MM5 can be found in Grell et al (1995). It is capable of being run non-hydrostatically with multiple nests. The model is also written to take advantage of multiple processors on shared-memory systems.

Support for 1999 SAT Experiment

In June of 1999 the Air Force Research Laboratory participated in the Scintillometer Atmospheric Test. The purpose of the experiment was to test the scintillometer newly installed on the Argus research aircraft. The experiment plan was to fly approximately ten missions in the New Mexico region. To help with the calibration of the airborne scintillometer, balloon measurements of refractive index were also made from the White Sands Missile Range. To provide support for the experiment it was decided to run the coupled MM5-Dewan et al. (1993) models in real-time and provide the forecasts to the mission planners. In addition to supporting the field program, the extensive exercise of the models also allowed their robustness to be evaluated.

To run the model in real-time, analyses and forecasts from the National Center for Enivironmental Prediction (NCEP) Eta model were used to provide initial and lateral boundary conditions for the MM5 run. NCEP posted the Eta files at its data archive site (ftp.ncep.noaa.gov) usually within three hours of the model initialization of 0000 and 1200 UTC. The Eta files contained an analysis for the initialization time and forecasts for the subsequent 3-h intervals out to 48 h. The Eta model output was available on 12 km horizontal grid and covered the continental United States. To automate the process of acquiring the Eta data, running the model and post processors, and delivering the output to the meteorologist briefing the mission planners, multi-layered C-shell scripts were written. The first script was submitted into the job queue on the Cray C90 at NAVO. The script was set to run at either 0300 UTC, for the 0000 UTC run, or 1500 UTC for the 1200 UTC run of the Eta model. Using the UNIX command, 'date', variables can be established to help create the file names for the day and time the script is being executed. Using a batch file that is constructed in the script, an ftp session was initiated to the NCEP's data archive site to copy the files back to the Cray C-90. If the files were not available the script submitted a new job to the job queue to start 20 minutes latter. After downloading the files to the NAVO fileserver, the script spawns off other scripts to run the MM5 pre-processors, REGRID (to horizontally interpolate the Eta fields to the MM5 grid) and INTERP (to vertically interpolate the Eta fields to the MM5 grid). Following successful completions of these scripts, another script was constructed and submitted to the queue to run the MM5 model and the Dewan et al. (1993) models. Further post processing was done to output the MM5 and optical turbulence fields in Grid Analysis and Display System (GrADS). After the data fields were in GrADS format, a ftp session driven by a batch file created by the previous script sent the output files to a fileserver available to the weather briefer. The last thing the script did was submit a new job to the queue for the next 12-hour run of the ETA model. Since the scripts able to use ftp batch files and the UNIX 'date' command to create file names, the jobs ran automatically without any user input.

While MM5 can be run for several nests and at very fine grid spacing, the real-time nature of the experiment necessitated several constraints on the model configuration. In order to insure timely running of the model it had to be executed on the express queue which limited total CPU time to 14,400 s. To insure the model ran within this time a single nest was used, with a 55x55 domain (Fig. 1) at 30 km horizontal grid spacing and 44 vertical levels. Another limitation was due to the use of the NCEP data. It was only available up to 50 mb, while it would have been preferred to go to 10 mb. The MM5 model was set to use up to 16 processors and generally averaged use of 9 processors on the shared memory C-90.

The timeline for each mission is listed in Fig. 2. The aircraft was scheduled to take off for each mission at 0800 UTC. The optical turbulence forecasts needed to available to the Staff Meteorologist briefing the mission planners approximately 2 hours prior to his 0600 UTC briefing. In order to insure that optical turbulence forecasts were available for the briefing, it was decided to run the combined models twice each day. Using data from the 1200 Eta run, a MM5-Dewan et al. (1993) model run would be initiated at 1500 UTC. The model would be initialized with the 1200 UTC fields and run out to 24 hours. Since this was in the late morning, there was quite a bit of competition for CPU resources and it sometimes took the model as long as 3 hours of wall-clock time to complete. This was not a problem since there was ample time before the pre-flight briefing. A second MM5-Dewan et al. (1993) model run was initiated off the 0000 UTC Eta fields available at 0300 UTC and integrated for 12 hours. Since this was at night when there was much less competition on the queue and the fact that model was integrated for 12 hours instead of 24, the model was usually complete within one hour of wall-clock time, which was just in time for the weather briefer's preparation.

Due to equipment and weather problems the actual flight schedule of the scintillometer was always in flux. Therefore it was decided to generate the model runs and forecasts continuously through the experiment period. The meteorologist responsible for the pre-flight weather briefings, reported that he made 12 pre-flight briefings (3 of the flights were eventually scrubbed). For all but two of the briefings he had access to the optical turbulence forecasts generated off the 0000 UTC (most recent) data. For the two other cases he was able to brief using the forecasts run 12 hours earlier. The format in which the data was provided (GrADS) proved to a good choice. All of the raw data was included in the files but was in a format that could be easily displayed using the GrADS software. This was especially useful since for some of the cases the weather caused the missions to be flown over Arizona. The weather briefer was able to quickly edit his GrADS scripts to alter his charts for briefing purposes. In addition to using the refractive index forecasts, he also used the forecast winds from MM5 in briefings. A sample of one of his briefing slides is given in Fig. 3. The staff meteorologist was very enthusiastic in his support of receiving the real-time optical turbulence forecasts. He felt that the MM5-Dewan et al (1993) forecasts gave him a good handle on the generation of optical turbulence from mechanical turbulence. He had other methods at his disposal to subjectively deduce optical turbulence from mountain waves and thunderstorms.

The series of runs of the MM5-Dewan et al (1993) models did point up some shortcomings. A dry convective adjustment was originally selected to use in the MM5 model runs but after several runs it became obvious that, in addition to being computationally expensive, it raised the risk of the model crashing to unacceptable levels. It was decided to turn the adjustment off. It was also found that since the Dewan et al. (1993) model uses different relationships for L based on whether the grid point is in the troposphere or stratosphere, a good method of determining the tropopause was needed. A tropopause identification routine based on the criteria published by Dewan and Good (1986) was installed. However, given the relative coarseness of the vertical resolution of MM5 used near the tropopause, criteria was not always met and in those cases a default value based on climatology was used.

Conclusions

A new method coupling a mesoscale numerical weather prediction model with an optical turbulence model has been described. Its application in the 1999 SAT experiment resulted in the first “operationally” produced objective optical turbulence forecasts. Even given the coarseness of the model’s resolution brought on by computer constraints, the model’s output was valued by its users. The extensive exercise of the MM5 and Dewan et al. (1993) models led to adjustments to increase the robustness and sensitivity of the forecasts. Work will continue to help determine the optimal configuration of MM5 to run with the Dewan et al. (1993) model. For this, the model results will be extensively compared with balloon-borne thermosonde measurements of C_n^2. Ultimately there will be a validation exercise of the current optical turbulence forecast models to see if they have the necessary accuracy for true operations or if a new generation of optical turbulence models will need to be developed.

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References

Bougeault, P., and P. Lacarrere, 1989: Parameterization of orography-induced turbulence in a meso-beta-scale model. *Mon. Wea. Rev.*, **117**, 1872-1890.

Bougeault, P., C. D. Hui, B. Fleury, and H. J. Laurent, 1995: Investigation of seeing by means of an atmospheric mesoscale numerical simulation. *Appl. Opt.* **34**, 3481-3488.

Dewan, E. M. and R. E. Good, 1986: Saturation and the "Universal" spectrum of vertical profiles of horizontal scaler winds in the atmosphere. *J. Geophys. Res.*, **91**, 2742-2748.

Dewan, E. M., R. E. Good, B. Beland, and J. Brown, 1993*: A Model for C_n^2 (Optical Turbulence) Profiles using Radiosonde Data.* Phillips Laboratory Technical Report, PL-TR-93-2043. ADA 279399.

Grell, G. A., J. Dudhia, and D. R. Stauffer, 1995: *A Description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5)*. NCAR Technical Note, NCAR/TN-398 + STR.

Hodur, R. M., 1997: The Naval Research Laboratory's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). *Mon. Wea. Rev.*, **125**, 1414-1430.

Imbard, M., A. Craplet, P. Degardin, Y. Durand, A. Joly, N. Marie, and J. F. Geleyn, 1987: Fine-mesh limited area forecasting with the French operational PERIDOT system. *The Nature and Prediction of Extra-Tropical Weather Systems*, European Center for Medium Range Weather Forecasts, Shinfield Park, Reading, UK.

Mellor, G. L. and T. Yamda, 1982: Development of a turbulent closure model for geophysical fluid problems. *Rev., of Geophys. and Space Phys.*, **20**, 851-875.

Tatarski, V. I., 1971: *The Effects of the Turbulent Atmosphere on Wave Propagation*, US Department of Commerce National Technical Information Service TT-68-50464.

Walters, D. L., and D. K. Miller, 1999: Evolution of an upper-tropospheric turbulence event – comparison of observations to numerical simulations. Preprints, *13th Symposium on Boundary Layers and Turbulence*, Dallas, TX.

Figure

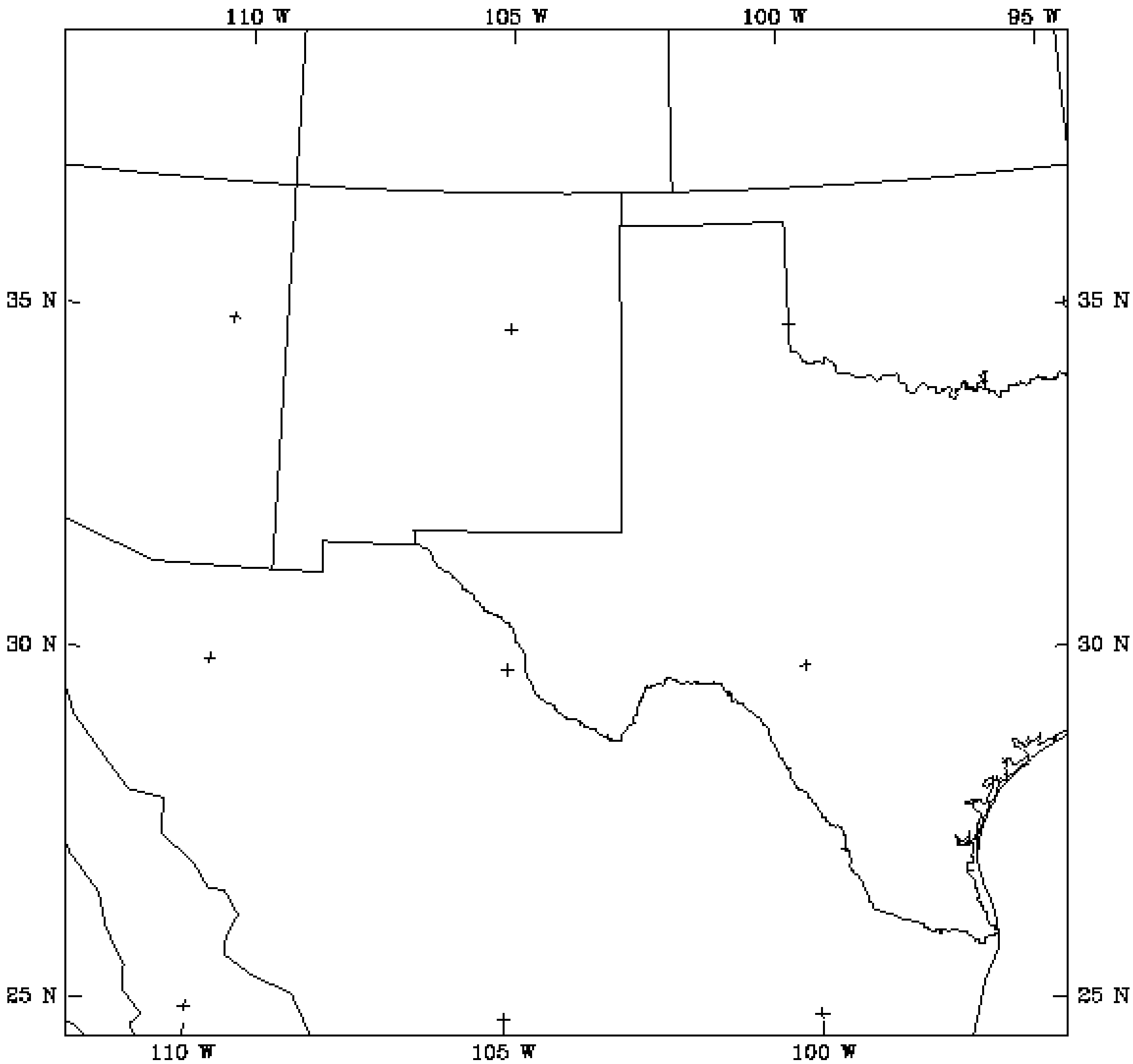

Fig. 1. Horizontal domain covered by the MM5-Dewan et al (1993) optical turbulence forecasts for the 1999 SAT experiment.

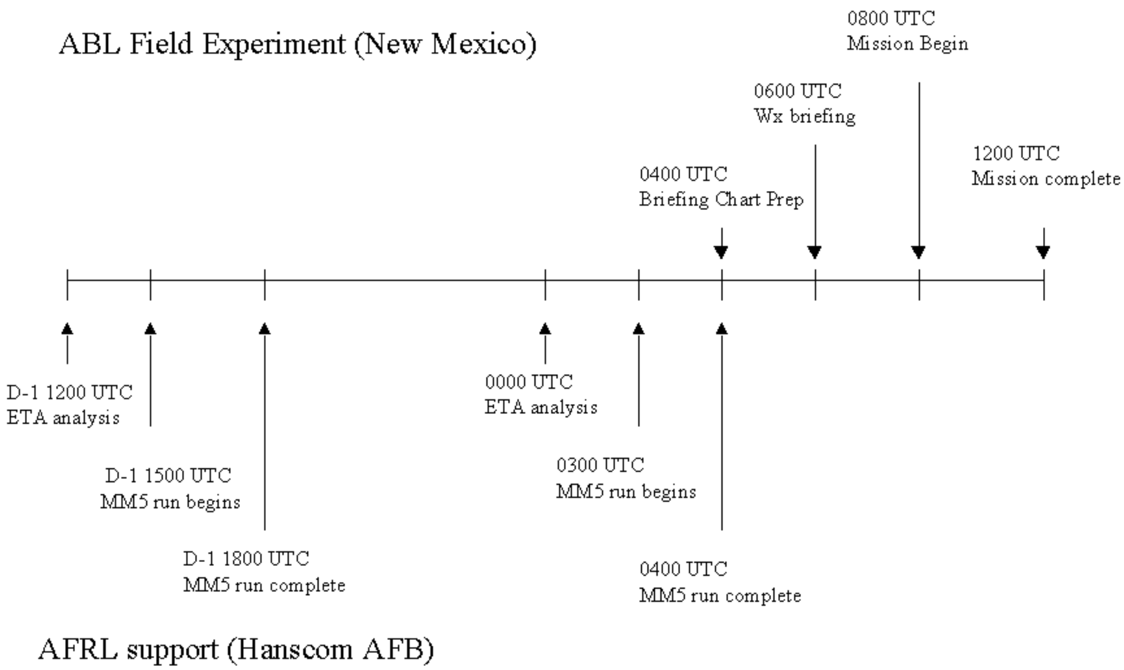

Fig. 2. Daily time lines for optical turbulence model and weather briefer forecasts for the 1999 SAT experiment.

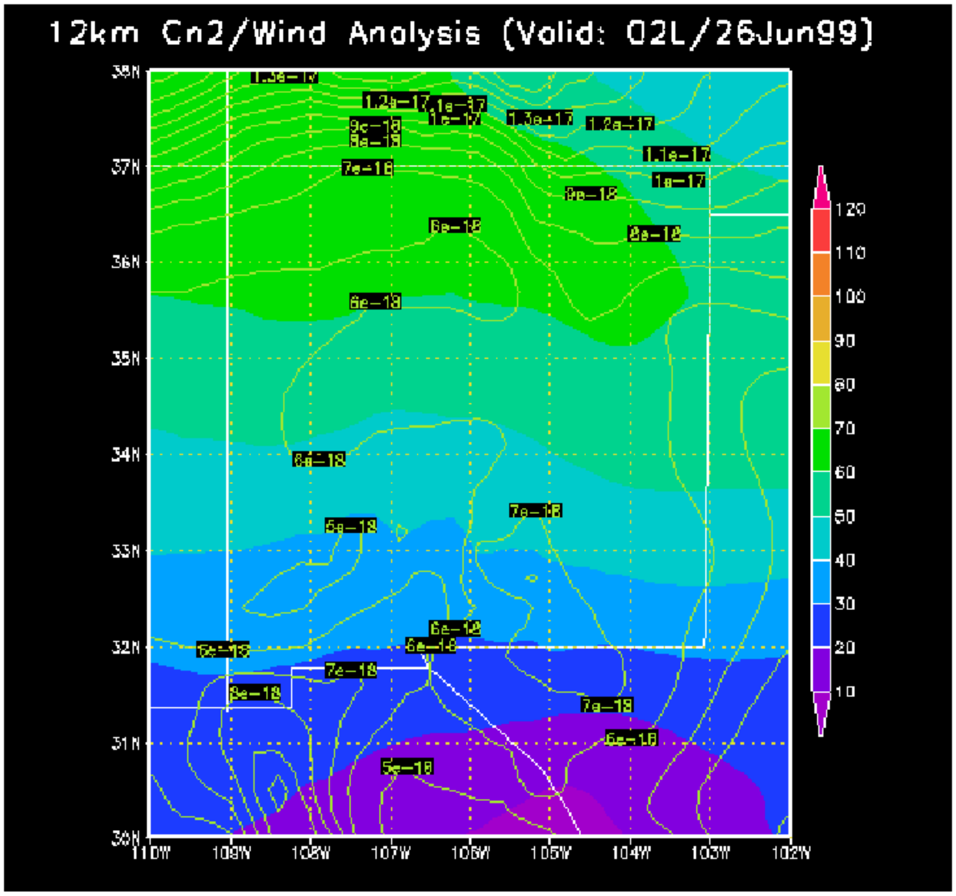

Fig. 3. Forecast at 12 km above MSL of C_n^2 (in $m^{-2/3}$) and winds (in ms^{-1}) on 26 June 1999 at 0800 UTC (0200 local).